—Review—

Forensic Examination of Soil Evidence

Yoshiteru Marumo

*National Research Institute of Police Science
6-3-1, Kashiwanoha, Kashiwa, Chiba 277-0882, Japan*

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Soil can provide important information to criminal investigations as transfer evidence because many criminal cases take place under circumstances such that soil transfers to a criminal or victim. The variation in soils from place to place makes soil valuable evidence to prove linkage between a suspect and a crime scene. Soil is a complex mixture with a variety of mineralogical, chemical, biological, and physical properties. Considering such complexity, a variety of methods have been developed for forensic science purposes. Because minerals are an important component of soils, mineralogical examination is essential in forensic soil identification. Additionally, many other methods can be applied to raise the discriminating power, but not all kind of methods need to be used. What is important is that examiners select an appropriate combination of methods by considering the context of the soil samples. This report summarizes a wide range of reports on the analysis of soil components and of closely related materials such as plant fragments, pollen and spores, and diatoms, with emphasis on the importance of screening tests consisting of several simple techniques. The soil formation process involves parent materials, temperature, water condition, vegetation, time, and the chemical processes of solution, oxidation, reduction, and even human activities. The history of a soil's development as the results of such complex soil formation process is strongly reflected in soil color. The systematic observation of multiple soil colors is especially useful for screening.

Key words: Forensic science, Soil identification, Soil color, Particle size distribution, Mineral, Botanic material

1. Introduction

Because of its ubiquitous nature as the surface of the earth, soil plays an important role as a type of transfer evidence that can establish linkage between a crime scene and a suspect. More than a hundred years ago, such a role for soil evidence in a criminal investigation was first described. But it was in a fictional story of the Sherlock Holmes series written by Sir Arthur Conan Doyle. At almost the same time, Hans

Gross of Austria wrote, in his handbook on criminalistics, that dirt on shoes could probably can yield useful information for a criminal investigation, but he did not include any actual case study or practical technology. According to a report by Murray¹⁾, Georg Popp of Germany might have been the first scientist who actually examined soil evidence, which led to the solution of a murder case in 1904.

The evidential value of soil rests on the large

variation in its characteristics from place to place. Soil has extreme complexity, not only in its components, such as minerals, oxides, organic matter, microorganisms, and parent materials, but also in its physical nature, such as particle size and density. Consider, for instance, soils with granite rock as their sole parent material. An almost unlimited number of kinds of such soils are easily recognizable by differences in color, mineralogy, and texture. Soil diversity is the result of soil formation processes acting on a variety of parent materials. These processes strongly depend on topography, climate, time, botanical and microbiological activities, water conditions, and even human activities. Moreover, there are millions of fossils, external matter such as pollen and spores, and even artificial materials that also contribute to the soil. Forensic soil examination is considered very complicated because of the complexity of soil, but such diversity allows us to identify soil samples with high discriminating power.

Because of the uniqueness of the forensic purpose and the complexity of soil, a great many methods for forensic soil examination have been proposed and discussed. Successful soil identification depends on examiners selecting a combination of methods suitable for the specific conditions of the soil evidence. The major object of this paper is to present an overview of forensic soil identification by summarizing the literature on the topic for the last three decades and to help forensic scientists select the best combination of methods appropriate for each case at hand. As soil particles are one of the major components of airborne dust, they frequently can be transferred if a suspect touched a dusty surface such as a door, windowsill, etc. This report, therefore, includes a discussion of dust and other earth-related materials such as plant fragments, diatoms, pollen, and spores.

2. Textbook and Review Papers

The monumental work in forensic soil investigation is the textbook entitled *Forensic Geology: Earth Science and Criminal Investigation* by Murray and Tedrow²⁾, which

was published in 1975. It has since been revised to include recent technological developments and has the title *Forensic Geology*³⁾.

Several handbooks and review papers have addressed the complexity and diversity of techniques available for forensic soil examination⁴⁻⁸⁾. The review paper by Demmelmeyer and Adam⁷⁾ discuss 178 reference reports that deal with (1) visual comparison of morphology, (2) preliminary examination with chemical reagents, (3) particle size distribution, (4) density gradient distribution, (5) polarized light microscopy, (6) further physico-chemical analysis, (7) biochemical components, and (8) vegetable trace materials. An overview paper⁹⁾ presented at the INTERPOL Forensic Science Symposium, which are held triennially, covers reports on technical developments of the previous three years.

3. Collection of Soil Samples

The significance of soil identification largely depends on the quality of sample collection; especially, the collection of control samples is very important. The improper collection of control soil samples will cause an incorrect judgment. Murray¹⁰⁾ reported his experience with 30 soil samples that, even though they had been collected systematically, were useless because they did not represent the exact original location of the questioned soil sample.

Because of the heterogeneous nature of soil, the significance of a match between questioned and control samples must be interpreted taking into account the intra-sample variations in the questioned samples and that in the control samples. Dudley and Smalldon¹¹⁾ suggested multiple sampling of control samples on the basis of their studies of simulated crime scenes. Lenth¹²⁾ and Evett^{13,14)} recommend the use of probability theory to evaluate soil evidence.

Munroe¹⁵⁾ has presented an excellent guide to sampling for forensic soil examination written from the pedological viewpoint that soil varies both in a horizontal and vertical direction. Control soil samples should be collected after careful visual inspection of soil color and texture

changes, both horizontal and vertical, and soil samples of different colors or textures should not be mixed even if they were taken from sites in close proximity. The soil sample should be kept unbroken as much as possible to preserve its structure. There is also a detailed description of sampling from a vehicle.

4. Macroscopic and Low-Power Microscopic Observation

Macroscopic and low-power microscopic observations are an important initial step in forensic soil comparison. Differences in the visual features between questioned and control samples mean that they originated from different locations, suggesting that any further examination is not necessary. If unique foreign particles, soil aggregates, or other trace evidence are found in soil samples, these particles should be removed and preserved separately for further examination¹⁶⁾. With luck, those unique particles may be found in both a questioned soil sample and a control one. Further examination can focus on these unusual materials in the soil, which at this step is regarded as only background of evidence.

Some interesting cases in which unique particles were the key to solving a crime have been reported. For example, in a murder case in California, the victim's body was abandoned at an oil-well apron, where gravel that had been transported from 300 miles further south had been used. In the soil evidence collected from a suspect's car, rock fragments were found and identified as having the same origin as those around the oil-well apron^{1,10)}.

Blue thread was decisive for solving a rape case in upper Michigan. Three flowerpots had been tipped over and the soil spilled on the floor in the struggle. Potting soil on the suspect's shoe was compared with that spilled from those flowerpots. Small clippings of blue thread were found both in the flower pot sample and on the shoe of the suspect¹⁾.

In a rape case in New Jersey, the rape took place in a vacant lot that had been used for a coal pile 60 years previously, and coal fragments

played an important role in the criminal investigation^{1,17)}.

A police officer who happened to look at a man arrested for a minor crime said "That's the worst case of dandruff I have ever seen." Later, it proved to be not dandruff but diatomaceous earth, and it compared species-to-species with the insulation material of a safe that had been ripped open on the previous day^{1,10)}.

In other murder cases, shell fragments in sand, lava fragments with distinctive features, and augite crystals with inclusions were key evidence in the criminal investigations.

5. Screening of Soil Samples

The significance of a match between questioned samples and control samples must be interpreted in light of the variations among the questioned samples and that among the control samples. The number of soil samples collected for comparison, therefore, must inevitably increase to obtain interpretations with evidential value. Simple and rapid screening methods are required for successful identification of a large number of soil samples. Color comparison and the determination of particle size distribution of soil samples can be carried out quite easily, and the combined data from those measurements can be quite useful for discriminating among samples.

5.1 Soil Color

Soil color, which reflects the pedogenic environment and history¹⁸⁾, is one of the most distinguishable characteristics of soil. Generally, the Munsell Color System is used for soil color determination, and the color is expressed by the combination of hue, value, and chroma. Soil Color Standards^{19,20)}, in which color chips from the Munsell Color System that cover the typical soil-color range are arranged, are widely used in the laboratory and the field.

Dudley²¹⁾ examined the usefulness of color examination for forensic soil discrimination, and proposed multiple color comparisons consisting of three color measurements for each soil sample, carried out on air-dried, moistened, and ashed (850°C, 30 min) sample. He concluded that

ashing had very good discriminatory potential, but moistening was less useful. Moistened soil color, however, should always be borne in mind, particularly when dry and ashed colors offer no possibility for discrimination.

Antoci and Petraco²²⁾ proposed the use of specially prepared paperboard for side-by-side comparisons of a soil sample directly with the standard color chips, and Janssen *et al.*²³⁾ proposed that color measurements should be carried out on the clay fraction in order to minimize variation caused by heterogeneity of the soil particles.

Color comparison of air-dried soil alone is insufficient for sample discrimination. Soil color can be seen as a result of a mixture of soil materials. Iron oxides give soil a reddish, brownish, or yellowish color, and humic substances make the soil darker. The parent materials also influence the soil color. Sugita and Marumo²⁴⁾ studied the usefulness of soil color for forensic examination in light of these pedogenic soil properties, and proposed a multi-step soil color comparison method, in which successive color determinations are made after air drying, moistening, decomposing organic matter, removing iron oxide, and ashing (850°C, 30 min). This method was applied to 73 soil samples collected systematically with reference to a geologic map and a land-use map²⁵⁾. In contrast to the results of Dudley²¹⁾, color after ashing did not raise the discriminating power, and moistening also did not allow effective discrimination among dark-colored soil samples with a value of less than 3 in the Munsell system. The combination of soil colors determined after air drying, decomposition of organic matter, and removal of iron oxides enabled up to 98% of the soil samples to be discriminated, compared with 84% by the single comparison of air-dried soil color. For comparison of color after decomposition of organic matter and removal of iron oxides, it is preferable to use clay fractions because of their homogeneity^{26,27)}.

5.2 Particle Size Distribution

Comparison of particle size, which is an apparent visible feature, is one of the more

important procedures when screening soil samples. The method generally used to separate particle size fractions is sieving, and the relative abundance of particles in different size ranges, the so-called particle size distribution, is useful to compare soil samples. Some of the factors that can affect the suitability of dry sieving for the determination of particle size distributions were studied by Wanogho *et al.*²⁸⁾. Dried soil samples, after decomposition of organic matter by hydrogen peroxide, were subjected to dry sieving with a sieve shaker. The results indicated that the larger the mass of the sample used, the better the degree of reproducibility. The most reasonable sample weight to adopt for analysis was 1 g or more. They concluded that the dry sieving technique was not preferred over wet sieving²⁹⁾. Factors affecting the suitability of wet sieving with a shaker, in comparison with dry sieving, were also studied by Wanogho *et al.*³⁰⁾ and Robertson *et al.*³¹⁾. The results by wet sieving showed less variation than those by dry sieving, but they concluded that simpler wet-sieving procedures were necessary because those using a shaker were rather complicated and required a large amount of sample.

Measurement of the particle size distribution of the finer particle size fractions of soils was studied by Dudley³²⁾, using a Coulter Counter, and by Wanogho *et al.*³³⁾, using a laser diffraction technique.

Dry sieving is easy to perform, but its reproducibility is poor if many aggregates are present in the soil samples. Clay, especially, strongly coagulates soil particles, therefore, dry sieving cannot be applied to the fine particle fraction. Wet sieving is required for fractions less than 0.05 mm in size. A study by Wanogho *et al.*³⁴⁾ indicated that wet sieving provides good reproducibility.

Marumo and Sugita^{35,36)} examined the validity of particle size distribution for forensic soil discrimination. As far as reproducibility is concerned, wet sieving is preferable. But to simplify the procedure, wet sieving should be employed only for the separation of the fine (< 0.05 mm particle size) fraction, and dry sieving

can be applied to the coarser particle fraction. In order to obtain better reproducibility for small soil samples, they recommended that only three particle size classes should be used: <0.05, 0.05–0.2 and 0.2–2 mm. The results of the examination of 73 soil samples collected systematically showed that 88% of samples could be discriminated by this method.

6. Density Gradient Distribution

The observation of distribution of soil particles in a density gradient column is the most traditional method used for forensic soil comparison. At present, however, only a few forensic science laboratories are using this method.

A density gradient tube is prepared by layering liquids of varying densities in a glass tube such that they gradually become less dense from the bottom to the top. Liquids of varying densities are made by mixing heavy and light liquids in various proportions. Generally, bromoform (2.89 g/mL) or tetrabromoethane (2.96 g/mL) is used as the heavy liquid, and bromobenzene (1.50 g/mL) or ethanol (0.789 g/mL) is used as the light liquid. A soil sample that has been dried and gently crushed is placed onto the density gradient tube³⁷⁾.

Many studies have been carried out with the intention of improving the reproducibility of the density gradient tube method^{38–40)}. However, careful studies by Chaperlin and Howarth⁴¹⁾ revealed that the comparison of density gradient patterns is very dependent on the observer, so reproducibility can be a problem. Murray and Tedrow³⁾ stated that the density gradient method has severe limitations, and little weight should be given to the results of this method.

Petraco and Kubic⁴²⁾ recently expanded the density gradient range from 2.89–1.50 g/mL to 4.24–1.00 g/mL by using Clerici's solution (CS, saturated solution of thallium malonate-formate) and distilled water (DS) instead of bromoform/bromobenzene or bromoform/ethanol. This density gradient column (CS/DS) can cover the whole density range of soil mineral particles.

7. Rock Fragments and Sand Particles

As the brownish color of soil mineral particles are mostly the result of staining by iron oxides, removal of iron oxides is required prior to mineralogical examination. Generally, Aguilera and Jackson's method⁴³⁾, in which sodium dithionite is used to reduce the iron oxides, is applied to the coarser particle size fractions of the soil. The 0.2–2 and the 0.05–0.2 mm fractions are examined for rock fragments and sand particles, respectively.

7.1 Rock Fragments

Rock fragments can provide useful information not only for sample-to-sample identification but also for predicting the original site of soil evidence, because rock fragments strongly reflect the geological characteristics of the soil. Rock fragments can be easily examined under a low-power binocular microscope without any sophisticated skill. The importance of this coarse soil fraction was thoroughly studied by Ugolini *et al.*⁴⁴⁾, who asserted that distinct mineralogical differences from site to site provide useful information to criminal investigations.

Soil evidence collected from a car floor is the most difficult evidence to evaluate by forensic science, because many different materials from different sites are brought into the car as the driver repeatedly gets into the vehicle. Nevertheless, if examiners discover rock fragments with distinctive features, these fragments can provide very important information to the criminal investigation. Rapp⁴⁵⁾ reported an interesting case in which small gravel found on the floor of the suspect's car played an important role in the criminal investigation.

7.2 Sand Particles

Microscopic examination of sand particles is an essential technique for forensic soil comparison because the sand fraction is one of the core components of soil, and mineralogical information on sand particles can be used to infer reasonable relationships between questioned soil samples and control ones. As examination of optical properties using a

polarizing microscope requires experience and skill, as well as long and tedious effort, recent studies for forensic purposes have tended to focus on simplification of the method. Heavy mineral composition is informative in forensic soil comparisons, but, as heavy minerals are not as abundant in soil, heavy minerals and light minerals should be subjected to mineralogical examination separately.

Graves⁴⁶⁾ has proposed a conventional microscopic method for forensic scientists to determine soil mineralogical composition. The classification of minerals into 38 categories is carried out by sequentially changing 14 optical conditions. Junger⁴⁷⁾ used an even more simplified classification system with 25 mineralogical categories. We use 15 categories: quartz, alkaline feldspars, plagioclase, volcanic glass, biotite, hornblende, hypersthene, augite, olivine, chlorite, zircon, magnetite, rock fragments, weathered particles, and other. Of course, mineralogical categories should be changed according to local variations and the specific geological and pedogenic situation. If unique minerals other than those categorized minerals exist in the soil samples, they should be recorded.

X-ray diffractometry (XRD) can also be applied to the identification of primary minerals. The amount of sample required for XRD can be reduced to 2 mg by using a quartz nonreflecting sample plate⁴⁸⁾. However, it should be noted that XRD cannot detect minor minerals composing less than 5% of the sample.

A staining method has been reported that simplifies light mineral identification⁴⁹⁾. Sequential treatment with potassium chloride, sodium cobaltinitrite, and hematein stains alkaline feldspars yellow and plagioclase purple, whereas quartz remains unstained.

An attempt has been made to use identification charts for mineralogical examination with a polarized microscope. Ishiwatari⁵⁰⁾ proposed a useful identification chart including 200 minerals for identification of minerals in rock specimens. If this identification chart were simplified for use with soil minerals, it

would be very useful for forensic soil examination.

Application of a scanning electron microscope equipped with an energy dispersive x-ray spectrometer (SEM-EDX) to mineralogical examination is the most promising approach for the future. McVicar and Graves⁵¹⁾ developed a particle search and analysis technique using an automated SEM-EDX system. Sand particles were identified according to mineral classification rules that had been formulated beforehand on the basis of the analysis of known minerals.

Park *et al.*⁵²⁾ attempted to apply image processing to pictures taken of sand particles under a polarized microscope. The color distribution calculated from the image processing was compared between soil samples. The results of this method do not completely correspond to the mineralogical composition, but it can be useful for sample-to-sample comparison.

The examination of sand particle morphology for forensic science purposes has been reviewed by Fitzpatrick and Thornton⁵³⁾.

8. Clay Minerals

Since clay minerals are secondarily produced in a soil pedon from parent materials during the soil-forming process, clay mineralogical composition reflects both the pedogenic environment and the parent material, such as sediments or metamorphic rocks. As clay minerals are too small for optical microscopy to be applied, identification of clay minerals relies on instrumental analyses. Marumo *et al.*^{54–58)} studied clay mineralogical analysis from the viewpoint of forensic science using XRD, infrared absorption spectrometry (IR), and differential thermal analysis (DTA). The particle size fraction less than 0.05 mm, after decomposition of organic matter and removal of iron oxides, was subjected to the instrumental analyses. As the crystals of most clay minerals have a platy structure, the basal spacings are recorded by XRD. For each soil sample, two kinds of oriented specimens were prepared from

magnesium-saturated (Mg-clay) and potassium-saturated (K-clay) clay. XRD was carried out on the Mg-clay specimen successively after air drying and after solvation with a glycerol solution, and on the K-clay specimen successively after air drying, after heating at 300 °C, and after heating at 600 °C. IR was successfully applied to clay specimens for the identification of gibbsite and kaolinite minerals. DTA was useful for identifying allophane, which cannot be identified by XRD or IR. The validity of the clay mineralogical analysis for forensic soil comparison was confirmed by applying these methods to soil samples collected from a region where all soils had developed from granite. As a result, the clay mineral composition showed variation reflecting topography⁵⁷).

McAlister and Smith⁵⁹) proposed a rapid technique for clay specimen preparation for XRD analysis whereby clay suspensions are precipitated onto membrane filter discs by syringe injection under pressure.

9. Organic Matter

The soil ecosystem contributes greatly to soil development, resulting in extreme soil diversity. There is incredible complexity in the soil ecosystem involving soil water, the cation-exchange and adsorption capacity of clay minerals, temperature, pH, soil atmosphere, solar radiation, oxidation-reduction potential, and legions of biological interactions⁴).

The simplest way to evaluate organic matter in soil is to measure total organic matter. Loss on ignition, which is measured by combusting soil samples using an electric furnace, can be useful to estimate total organic matter, although it includes a part of the crystalline OH of minerals and strongly absorbed water. Wanogho *et al.*^{28,29}) proposed to use the weight loss from the decomposition of organic matter with hydrogen peroxide, which is necessarily carried out prior to mineralogical examination. Demmelmeyer⁶⁰) proposed that total carbon content determined by using wet combustion with potassium bichromate would be representative of total organic matter.

Humic substances are a group of vastly complicated organic substances that are produced by biological decomposition of plant bodies and other biotic materials. A variety of analytical methods for humic substances have been proposed for soil science investigations, but all those methods are very complicated and time-consuming, and they require more than several grams of soil sample. Honna *et al.*⁶¹) developed a simple technique to evaluate humic substances, in which a soil sample (0.5–1 g) extracted with 0.5% sodium hydroxide is subjected to absorbance measurements.

The chromatographic pattern is a convenient method for comparing organic matter between soil samples. Siegel and Precord⁶²) and Reuland *et al.*⁶³) proposed the application of high performance liquid chromatography (HPLC) with reverse phase columns to soil extracted with organic solvents such as methanol or acetonitrile. Nakayama *et al.*⁶⁴) applied pyrolysis gas chromatography (PyGC) to 113 soil samples collected from Tokushima prefecture, and used mass spectrometry (MS) to further identify major peaks on the pyrogram. The pyrogram patterns showed good reproducibility within the same soil, and large variation among soil samples of different origin.

Cox *et al.*⁶⁵) recently developed an excellent method for analysis of soil organic matter using Fourier transform infrared absorption spectrometry (FTIR). The spectra were measured before and after pyrolysis, and the difference between the two spectra, which represented the organic matter in the soil, was used to compare soil samples. This method was applied to four soil samples which were indistinguishable by color and loss by ignition. All four soil samples could be clearly differentiated.

The usefulness of saccharide levels in soil has been discussed for a simulated crime scene¹¹), but the method has not yet been thoroughly studied for forensic science purposes.

10. Biotic Materials

10.1 Plant Fragments

Small fragments of plants in soil samples can be informative for forensic soil identification. Plant fragments are also frequently found on clothes or car floors, providing useful information about a link between a suspect and a crime scene. If leaves are in a good condition of preservation, it is not difficult to identify their species. The leaf epidermis is composed of epidermis cells, subsidiary cells, stomata, and hairs with a variety of shapes and arrangements; thus, microscopic observation allows us to compare plant fragment samples or identify species by referring to an atlas.

Hiroe⁶⁶⁾ examined a great number of monocotyledonous and dicotyledonous plants in Japan. In this study, specimens were prepared by peeling off the lower epidermis with sharp tweezers and observed under a compound microscope at a magnification of 100–400. Generally, however, plant chips that are encountered in forensic science laboratories are withered or partially decayed so that it is difficult to peel off the epidermis. Marumo *et al.*⁶⁷⁾ used a scanning electron microscope (SEM) to identify plant fragments directly. After plant fragment samples were softened by boiling in water, they were dipped in ethanol to remove the water and stretched on a filter paper for drying. Then, the fragment was cut into two pieces, and one of them was turned upside down so that both sides of the leaf could be seen on the same SEM sample holder.

Westerkamp and Demmelmeyer⁶⁸⁾ published an atlas of foliar leaves from trees and shrubs growing in Central Europe with 250 scanning electron micrographs and two diagrams. It includes a list of their morphological characteristics, species distribution, and habitat requirements. An atlas of scanning electron micrographs of Japanese Gramineae grass was published by Marumo *et al.*⁶⁹⁾ It includes pictures of both upper and lower epidermis at a magnification of 100–500 of 89 species. Bock *et al.*⁷⁰⁾ published a guide to food

plant cells for use in criminal investigations and pathology. They utilized characteristic features of epidermis cells of plants, especially those of food plants, to identify the stomach contents of homicide victims⁷¹⁾.

10.2 Plant Opals

If soil samples are brought from different sites but have similar mineralogical compositions, they cannot be distinguished by petrological techniques. Plant opal examination can be a useful approach to solve such a problem, because plant opals in soils are dependent principally on vegetation and are independent of geological materials⁷²⁾. Surface soil contains silica particles called plant opals or opal phytoliths, which are formed through progressive silicification of cells in plant bodies. As plant opals are casts of plant cells, they have a variety of unique shapes, especially those formed in the monocotyledonous grasses have species-specific morphology. Kondo, and Sase and Kondo^{73–75)} have proposed a classification system for gramineous plant opals comprising seven classes: festucoid (boat-shaped); panicoid (dumbbell-shaped); chloridoid (saddle-shaped); bambusoid (acutely angled outlines); fan-shaped (fan-shaped or rectangular outline); elongate; and point-shaped classes.

Generally, light particles with a density of less than 2.3 separated by heavy liquid (bromoform/ethanol) from the 0.01–0.2 mm fraction are subjected to observation for plant opals under a compound microscope at magnifications of 100–400. Sugita has simplified the procedure to use the <0.05 mm fraction, from which clay minerals have been previously removed by sedimentation, instead of using the heavy-liquid separation technique. These procedures can also be used to prepare soil samples for examination of diatoms.

10.3 Diatoms and Microfossils

Diatoms are frequently observed in soil, since they can rapidly propagate in various environments even during temporary wet conditions. Because of the distinctive diversity of diatom species and assemblages, diatoms can provide useful information for forensic soil

identification⁷²⁾. A series of articles about diatoms entitled “Diatoms: diatom microscopy” appeared in the journal *Microscope*⁷⁶⁾. Regarding Japanese diatom flora, a textbook originally written by Kawamura and edited by Ueno⁷⁷⁾ is useful. These resources will be helpful to forensic scientists who are interested in diatoms as trace evidence.

Diatom tests have also been used for the postmortem diagnosis of drowning⁷⁸⁾. Although there have been many reports on the use of diatoms to diagnose drowning^{79–86)}, the details will not be discussed here.

Soil where sand from alluvial or diluvial deposits has been used for construction may contain microfossils. Kurata and Hirano⁸⁷⁾ found small cylindrical particles in soil samples when they were dealing with evidence from a criminal case. Detailed study revealed those particles to be Bryozoa fossils, which had been in the sand materials used in the construction of a building. Such unique fossils can be useful for determining the location where the soil evidence originated.

10.4 Pollen and Spores

Criminal investigations require forensic pollen analysis to establish the presence or absence of localized pollen species in soil evidence. For this purpose, species of forensic interest are generally insect pollinated, and not wind pollinated. Pollen of insect-pollinated species tends to remain near the site of deposition of their flowers, whereas wind-pollinated species disperse pollen long distances and distribute it over an extensive area. A useful protocol was provided by Eyring⁸⁸⁾, who made some modifications to traditional methods. Eyring describes a detailed procedure for pollen specimen preparation for microscopic observation, and includes important references about pollen extraction and identification, pointing out that pollen in soil is sometimes stained or has altered features.

Variation in pollen assemblages in surface soils from site to site was examined by Horrocks *et al.*⁸⁹⁾. Samples from within the same localized area showed a high degree of similarity. On the

other hand, pollen assemblages from different places, even with similar vegetation, showed significant differences within the same geographic region. They also confirmed the validity of pollen analysis for comparison of soil samples from shoes with those from places where shoeprints were impressed⁹⁰⁾. Bruce and Dettmann⁹¹⁾ discussed pollen/spore assemblages in surface soils of Queensland, Australia.

Several case reports describing the successful application of pollen analysis to criminal investigations are available. Horrocks and Walsh⁹²⁾ reported a rape case to which pollen analysis was applied. Soil samples taken from the jacket and pants of a suspect were compared with soil at the crime scene and soil from where the suspect's car was parked. The suspect had insisted that although he certainly had been there, he had stayed beside his car without running after the victim. But the results of the pollen analysis strongly supported the suspicion of guilt because the pollen assemblages in the samples from the suspect correlated with those in the soil of the crime scene.

In the case of a private airplane crash near Ruidoso, New Mexico, in 1989, the problem was to determine whether a small mass of biotic materials isolated from the fuel assembly had formed before or after the accident. In this case, pollen analysis and soil examination played an important role by showing that the biotic materials had formed during storage of the crashed airplane^{93–98)}.

10.5 Microbiology

Although it has been said that soil is a treasury of microorganisms, reports about microbiological techniques for forensic soil comparison are very rare. Thornton *et al.*⁹⁹⁾ proposed a biochemical approach to forensic soil comparison. They proposed to measure the activity of phosphatase, arylsulfatase, urease, trypsin, and invertase by colorimetric and titrametric methods as essential indices of biological activity in soils. The Michaelis constant (K_m) is considered to be particularly significant because it is independent of sample size. But it should be noted that because enzyme

activities fluctuate and shift with time, the soil evidence and exemplar soil must be collected at approximately the same time.

Omelyanyuk *et al.*¹⁰⁰⁾ proposed a multisubstrate testing method for forensic soil comparison. In this method, 11 carbon sources such as lactose, acetate, etc. are used for incubation of microorganisms in soil extract, and the growth of microorganisms is monitored by using the color reaction with tetrazolium violet.

11. Instrumental Analysis

Studies on the application of elemental analysis to forensic soil identification have been attempted using x-ray fluorescence spectrometry (XFS). Hiraoka¹⁰¹⁾ studied discrimination of soils with energy dispersive XFS using 110 soil samples collected from Kyoto prefecture in Japan. Statistical evaluations revealed that concentrations of rubidium, strontium, potassium, and iron showed good correlation with geological materials at the sampling sites. These results suggest that elemental analysis by XFS could be useful for determining the original location of soil evidence.

As Thornton⁴⁾ has pointed out, the interpretation of elemental data will remain somewhat clouded because of the heterogeneity of elements in soils. Elemental analysis requires relatively large amounts of sample (several grams) and is not applicable to trace soil evidence. Since elements exist in different forms in the soil, it is preferable to use an analytical method specific to those chemical forms. For forensic science purposes, Marumo¹⁰²⁾ studied a simplified method that used XFS to determine free oxides of iron, aluminum, and silicon in soils. A dithionite-citrate system buffered with sodium bicarbonate (Mehra and Jackson's method) and an acidic ammonium oxalate system (Tamm's method) were used to extract different type of oxides. Mehra and Jackson's method can extract both amorphous and crystallized oxides, and Tamm's solvent dissolves amorphous oxides. The conditions under which a soil developed are strongly

reflected in the composition of those oxides, allowing us to differentiate soil samples. The application of various instrumental analyses of elements in soil has been summarized by Bain *et al.*¹⁰³⁾.

Thermoluminescence (TL) is the emission of light when a material is heated to temperatures just below incandescence. TL curves recorded as light intensity versus temperature depend on the particular materials involved and their minor components and on environmental history such as radiation and thermal and pressure conditions. Ingham and Lawson¹⁰⁴⁾ studied the application of TL to forensic soil comparison. Samples were exposed to radiation from cesium-137 or cobalt-60, and then TL curves were measured. The results for 630 samples showed a coincidental match of only 2.3%.

High performance liquid chromatography (HPLC) of organic compounds in soil has been studied by Nilsson¹⁰⁵⁾ and Andrasko¹⁰⁶⁾. They proposed that the analysis of polycyclic aromatic hydrocarbons (PAH) would be useful for forensic soil identification. PAHs, which have two or more benzene rings, are produced by combustion or pyrolysis of fossil fuels and other organic materials. An analysis of PAHs in systematically collected soil samples showed significant discriminating power. Reuland and Trinler¹⁰⁷⁾ studied HPLC analysis for forensic soil identification and emphasized that if constituents that exist only under certain ecological conditions are found in soil samples, that evidence will greatly assist in police investigations.

Cengiz and Sakul¹⁰⁸⁾ reported on the application of anion analysis to forensic soil discrimination. Capillary electrophoresis was applied to soil extract. Chlorite, nitrate, sulfate, and phosphate contents were compared among soils.

A successful pH measurement method for soil evidence using a colorimetric technique has been developed by Dudley¹⁰⁹⁾.

12. Other

12.1 Ceramics and Concrete

Hashimoto *et al.*¹¹⁰⁾ reported an appropriate method for forensic identification of ceramics. Their results showed that sulfuric acid etching yields favorable results for micromorphological observation by SEM.

In a murder case, a corpse was embedded in concrete, and a bucket to which concrete was adhered was found in a suspect's home. Visual examination of cross-sections of concrete fragments under a binocular microscope and elemental analysis by XFS successfully identified the concrete fragments.

12.2 Dust

Because dust is a complex mixture of various distinctive types of particles and fibers, it can hold rich information for criminal investigations. If a particular combination of some unique components in dust can be established, it can be strong proof of contact with a particular place. Millette and Few¹¹¹⁾ described five basic dust-sampling methods suitable for obtaining samples for microscopic analysis, with illustrations of samplers and a list of 30 useful references on dust sampling. The five basic sampling methods are brushing, scraping, lifting with adhesive tape, wiping, and vacuuming. One-liter ziploc plastic bags are part of an effective technique proposed for collecting settled dust for microscopy in almost any situation¹¹²⁾. The bag is used as a collection glove, and then the dust is preserved in the bag until examination.

Millette and Few¹¹³⁾ also investigated indoor carbon soot particles using transmission electron microscopy. They were able to classify carbon soot into four groups: (1) carbonized wood or cellulose materials ranging from micrometers to millimeters in size and often retaining some of the features of the original materials; (2) hard, shiny porous or hollow carbon spheres, typically 10–100 μm in diameter; (3) spherical or near-spherical particles with mean diameters of around 20 to 30 nm adhering to each other to form straight or branched chains; and (4) spheroidal carbon particles of colloidal

dimensions.

Benko¹¹⁴⁾ described polarized microscopic observation and FTIR analysis of dust. Cooking grease, vegetable oils, some candle wax formulations, and certain semivolatiles may provide definitive spectra. Residues from cleaning/polishing products also gave unique IR spectra.

13. Case Studies

On 16 March 1978, the prime minister of Italy, Mr. Aldo Moro, was kidnapped on his way to the Parliament House. In the morning of 8 May 1978, Mr. Moro's body was found in the trunk of a car. The results of the forensic investigation were disclosed after 20 years. Lombardi¹¹⁵⁾ discussed the findings of the forensic investigation conducted on the evidence found on Mr. Moro's clothes and shoes (beach sand, bitumen, vegetable materials, and polyester fragments), and in/on the car. The study of the vegetable materials suggested that they had been picked up at a time close to the killing. Thermosetting polyester, of the type used in boat manufacturing, was found under the fenders, in the tires, and inside the car, as well as under Mr. Moro's shoes, supporting proximity of a beach. Pollen analysis showed that the adhesion of volcanic soil to the car fenders antedated the adhesion of the sand.

In November 1989, an aircraft flew from San Diego, California, toward Ruidoso, New Mexico. The aircraft crashed a few moments before a scheduled landing near Ruidoso in Lincoln County, New Mexico. The contribution of soil evidence to the investigation of this case was reported by Daugherty⁹⁸⁾. Because the plane had been exposed to intense fire after the crash, the change in soil color by heating was examined by using a redness rating test, which can illustrate the relation between reddening and heating of soil samples.

14. Conclusion

Because sand and clay are core components of soils, their mineralogical examination is certainly inevitable. More important for forensic

soil identification, however, are screening tests of soil samples. Soil color and particle size distribution tests are easy to perform and have high discriminating power when used in combination. Especially, soil color, in which both soil development conditions and mineralogical composition are reflected, has an importance almost equivalent to that of soil mineralogy in forensic soil identification. Soil color can be regarded as a mixture of humic substances, iron oxides, and minerals. Therefore, soil color must be observed step by step, before any treatment (air-dried sample), after decomposition of organic matter, and after removal of iron oxides. Additionally, observation of moistened and of ashed (850°C, 30 min) soil can occasionally raise the discriminating power.

Observation of coarse particles (0.2–2 mm) and rock fragments using a binocular microscope is also easy to perform and effectively raises the discriminating power of the screening. These methods mentioned above are essential for forensic soil examination. However, since a variety of soil samples are encountered in forensic science laboratories, many other methods can optionally be used, taking into account conditions specific to individual soil samples. To cover such a diversity of soil, many more studies on soil identification, carried out from various points of view, are anticipated.

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